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Fakultät Physik
Theoretische Physik III

R-Parity violating flavor symmetries and absolute neutrino mass scale

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R-parity violation (RPV) $\boxed{R_P = (-1)^{3(B-L)+2S}}$

- LSP is no longer stable
- New superpotential operators and soft terms

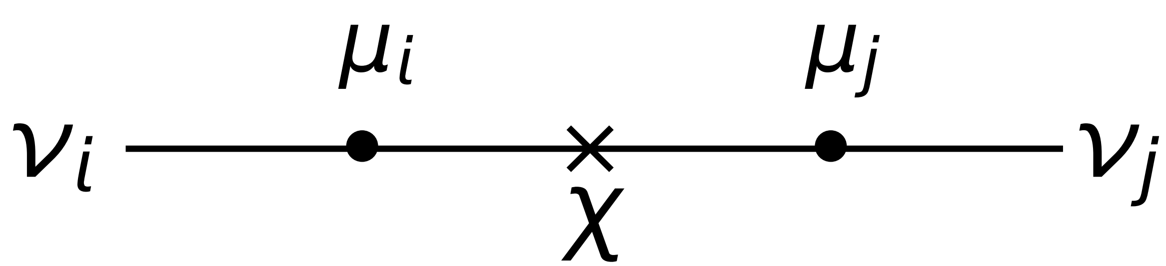
$$W_{RPV} = \mu_i L_i H_u + \frac{1}{2}\lambda_{ijk} L_i L_j E_k^C + \lambda'_{ijk} L_i Q_j D_k^C + \frac{1}{2}\lambda''_{ijk} U_i^C D_j^C D_k^C$$

$$V_{RPV}^{\mathrm{soft}} = B_i h_u \tilde{L}_i + \frac{1}{2} A_{ijk} \tilde{L}_i \tilde{L}_j \tilde{e}_k^C + A'_{ijk} \tilde{L}_i \tilde{Q}_j \tilde{d}_k^C + \frac{1}{2} A''_{ijk} \tilde{u}_i^C \tilde{d}_j^C \tilde{d}_k^C + \tilde{m}_{di}^2 h_d^\dagger \tilde{L}_i$$

  - Lepton and/or baryon number violation
  - Different collider signatures

Neutrino masses

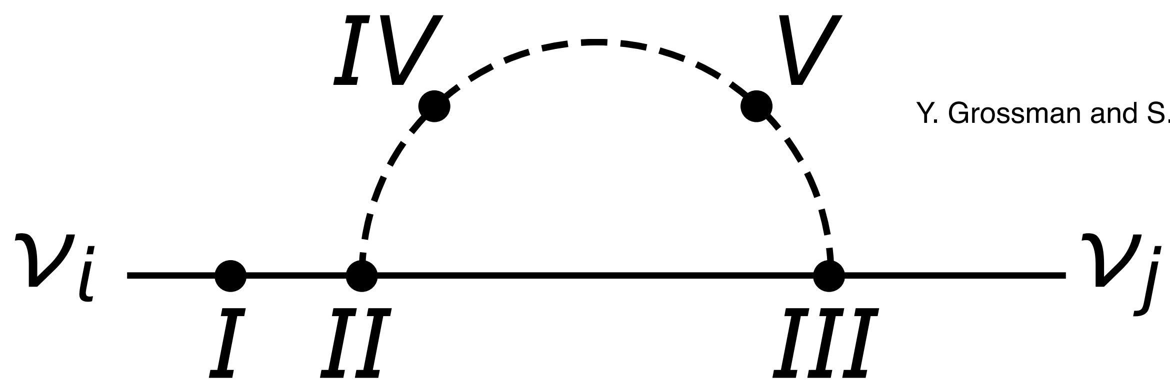
- Neutrino/neutralino mixing via the bilinear Operator



$$\approx \frac{\cos^2\beta}{\tilde{m}}\mu_i\mu_j$$

- Only one massive neutrino at tree level
- Loop contributions via several combinations of bi- and trilinear couplings
- Three mass eigenvalues at 1-loop level

Neutrino masses



Y. Grossman and S. Rakshit, Phys. Rev. D 69 (2004) 093002

$$I + III \approx \sum_k \frac{3g}{16\pi^2} m_{d_k} \frac{\mu_i \lambda'_{jkk} + \mu_j \lambda'_{ikk}}{\tilde{m}} \qquad I + V \approx \frac{g^2}{64\pi^2 \cos\beta} \frac{\mu_i B_j + \mu_j B_i}{\tilde{m}^2}$$

$$II + III \approx \sum_{l,k} \frac{3}{8\pi^2} \lambda'_{ilk} \lambda'_{jkl} \frac{m_{d_l} m_{d_k}}{\tilde{m}_q^2} \mu \tan\beta \qquad IV + V \approx \frac{g^2}{64\pi^2 \cos^2\beta} \frac{B_i B_j}{\tilde{m}^3}$$

Approximations

- Left/right squark mixing in trilinear loops $\Delta m^2_{\tilde{d}_k} \approx m_{d_k} \mu \tan\beta$
- A common squark mass scale $\tilde{m}_q$
- A common mass scale $\tilde{m}$ for other involved sparticles

A generic flavor symmetry

- Goal: reduce the number of independent RPV couplings
  - Preserve the ability to generate neutrino masses and mixing
- We don‘t aim to explain the charged lepton and quark sector
- Baryon number is conserved to prevent rapid proton decay
  - All λ'' couplings are forbidden

A generic flavor symmetry

- Symmetry conserves lepton number
  - only leptons are charged
  - Breaking introduces LNV and LFV
- LNV bi- and trilinear couplings depend on operator charge Q and breaking parameter ϵ
- Coupling suppression:

$$\mu_i \sim \tilde{\mu}\epsilon^{Q(L_i)} \quad B_i \sim \tilde{m}^2\epsilon^{Q(L_i)}$$
$$\lambda'_{ijk} \sim \epsilon^{Q(L_i)} \quad \lambda_{ijk} \sim \epsilon^{Q(L_i)+Q(L_j)+Q(E_k^C)}$$

2 generic assumptions

- Only leptons are charged under the symmetry
  $Q(L_i Q_j D^C_k) = Q(L_i H_u) = Q(L_i) \Rightarrow \lambda'_{ijk} \rightarrow \lambda'_i \rightarrow \mu_i$
- The charges obey the relation $Q(L_i) = -Q(E^C_i)$
  $Q(L_i L_j E^C_j) = Q(L_i) \Rightarrow \lambda_{ijj} \rightarrow \lambda'_i \quad (i \neq j)$
  - Only 3 totally antisymmetric λ couplings remain independent
  - 6 independent couplings

Remaining Couplings

- 3 bilinear and 3 totally antisymmetric trilinear independent couplings left
- Dependent couplings aligned with the bilinear couplings
- Tightest bound for any of the dependent single couplings/coupling pairs translates to all others

Ind. Couplings	Dependencies
μ_1	$B_1,\ \lambda'_{1jk},\ \lambda_{1jj}$
μ_2	$B_2,\ \lambda'_{2jk},\ \lambda_{2jj}$
μ_3	$B_3,\ \lambda'_{3jk},\ \lambda_{3jj}$
λ_{123}	-
λ_{132}	-
λ_{231}	-

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Single coupling bounds

Couplings	Bound	Scaling
$\mu_1/\tilde{\mu},\ \mu_2/\tilde{\mu},\ \mu_3/\tilde{\mu}$	$\mathcal{O}(10^{-5})$	$100\,\mathrm{GeV}/\tilde{\mu}$
$\lambda_{123},\ \lambda_{132},\ \lambda_{231}$	0.05	$m_{\tilde{e}_{kR}}/100\,\mathrm{GeV}$

Y. Kao and T. Takeuchi, arXiv:0910.4980 [hep-ph]

- Bilinear couplings constrained by neutrino masses (basis of vanishing neutrino VEVs)
- Lambda couplings constrained by

$$\left.\frac{\Gamma(\tau \to e\overline{\nu}_e\nu_\tau)}{\Gamma(\tau \to \mu\overline{\nu}_\mu\nu_\tau)}\right|_{SM} = 1.028,\quad \left.\frac{\Gamma(\tau \to e\overline{\nu}_e\nu_\tau)}{\Gamma(\tau \to \mu\overline{\nu}_\mu\nu_\tau)}\right|_{EXP} = 1.028 \pm 0.004$$

Coupling combination bounds

- All other bounds for combinations of dependent trilinear couplings easily satisfied
- Combinations of the totally antisymmetric couplings only constrained by neutrino masses
- Relevant constraints from $K_L^0 \rightarrow \mu\bar{e}/e\bar{\mu}$

$$\lambda_{312}\lambda'_{312} < 6.7 \times 10^{-9} \frac{m^2_{\tilde{\nu}_{L3}}}{(100\,\mathrm{GeV})^2} \qquad \lambda_{312}\lambda'_{321} < 6.7 \times 10^{-9} \frac{m^2_{\tilde{\nu}_{L3}}}{(100\,\mathrm{GeV})^2}$$

$$\lambda_{321}\lambda'_{312} < 6.7 \times 10^{-9} \frac{m^2_{\tilde{\nu}_{L3}}}{(100\,\mathrm{GeV})^2} \qquad \lambda_{321}\lambda'_{321} < 6.7 \times 10^{-9} \frac{m^2_{\tilde{\nu}_{L3}}}{(100\,\mathrm{GeV})^2}$$

H. K. Dreiner, M. Kramer and B. O'Leary, Phys. Rev. D 75, 114016 (2007)

Neutrino masses so far

- All but contributions involving totally antisymmetric lambda couplings are aligned with tree level contributions and can be absorbed in a constant

$$m_{ij}^{\mu\mu} = C\mu_i\mu_j, \;\; C \simeq \frac{\cos^2\beta}{\tilde{m}} + \sum_k \frac{3gm_{d_k}}{8\pi^2\tilde{m}^2} + \sum_k \frac{gm_{e_k}}{8\pi^2\tilde{m}^2} + \sum_{k,l} \frac{3m_{d_l}m_{d_k}}{8\pi^2\tilde{m}\tilde{m}_q^2}\tan\beta$$

- This assumes $\tilde{\mu} = \tilde{m}$ and drops the B-contributions
- Reasonable approximation for nearly degenerate sneutrino masses, due to $B_i \sim \mu_i$ and Higgs-cancelations

Neutrino masses so far

- Contributions to diagonal elements from totally antisymmetric couplings

$$m_{ee}^{\lambda\lambda} = \frac{1}{8\pi^2}\lambda_{123}\lambda_{132}\frac{m_\mu m_\tau}{\tilde{m}^2}\mu\tan\beta, \quad m_{\mu\mu}^{\lambda\lambda} = \frac{1}{8\pi^2}\lambda_{213}\lambda_{231}\frac{m_e m_\tau}{\tilde{m}^2}\mu\tan\beta$$

$$m_{\tau\tau}^{\lambda\lambda} = \frac{1}{8\pi^2}\lambda_{321}\lambda_{312}\frac{m_\mu m_e}{\tilde{m}^2}\mu\tan\beta$$

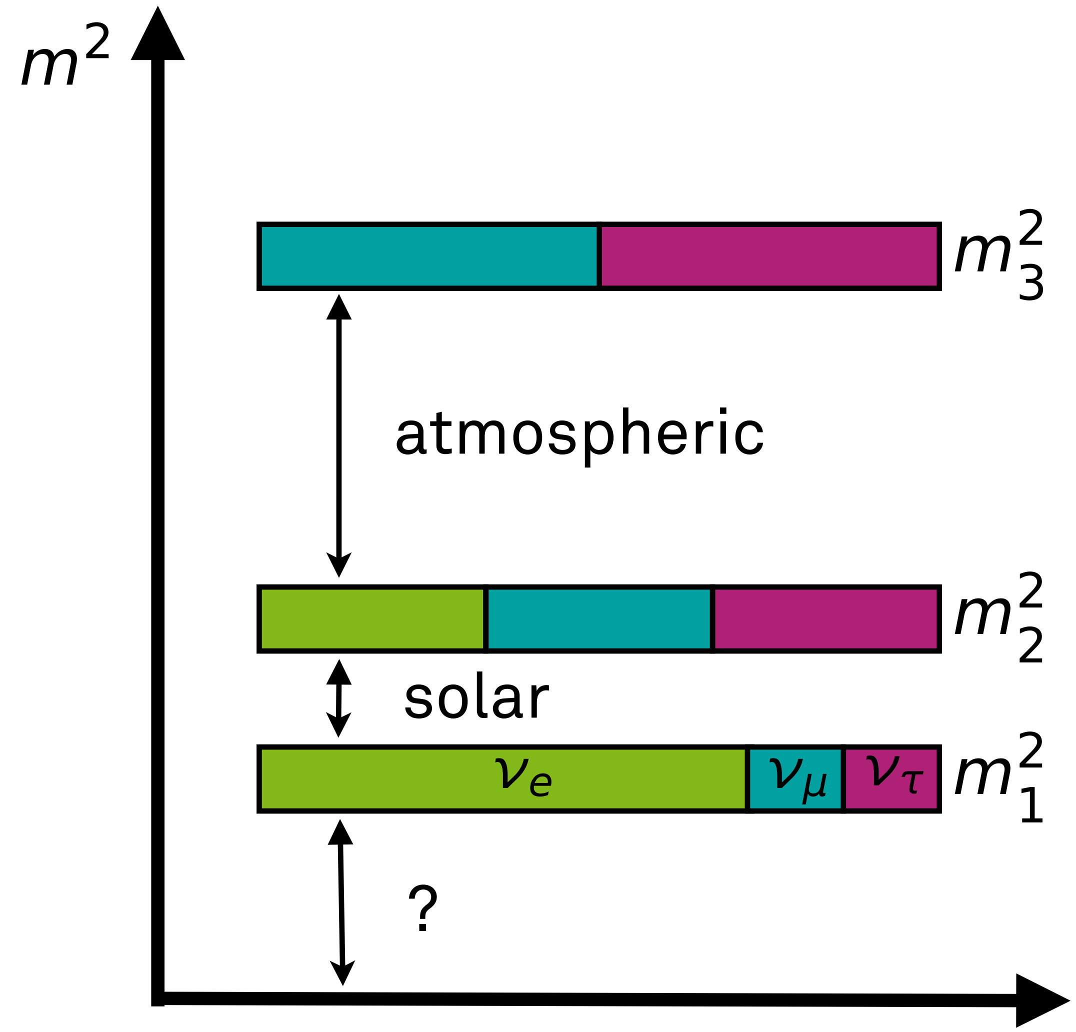
- Possibly relevant offdiagonal contributions

$$m_{e\mu}^{\lambda\lambda} = \frac{1}{8\pi^2}\lambda_{123}\lambda_{232}\frac{m_\tau m_\mu}{\tilde{m}^2}\mu\tan\beta, \quad m_{e\tau}^{\lambda\lambda} = \frac{1}{8\pi^2}\lambda_{132}\lambda_{323}\frac{m_\tau m_\mu}{\tilde{m}^2}\mu\tan\beta$$

- Contributions proportional to one small coupling and the electron mass are irrelevant

Experimental Access

- PMNS Matrix parametrized by 3 mixing angles and 3 phases
- Access to the mixing angles and mass squared differences via oscillation experiments
- Upper bounds for the absolute neutrino mass scale
- Undetermined hierarchy, unconstrained phases
- Recent evidence from MINOS and T2K for large θ_{13}
- Tribimaximal mixing (TBM) not yet ruled out



$$V_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

Four Scenarios investigated

- Consider the following scenarios
  - TBM vs. $\theta_{13} = 9°$
  - Normal hierarchy vs. inverted hierarchy
- Dirac- and Majorana phases vanish
- The smallest mass eigenvalue is set to zero
  - How much potential is there for larger mass eigenvalues?
  - What is the limiting factor?

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IH, TBM

$$m = \begin{pmatrix} 4.92 \times 10^{-2} & 2.56 \times 10^{-4} & -2.56 \times 10^{-4} \\ 2.56 \times 10^{-4} & 2.47 \times 10^{-2} & -2.47 \times 10^{-2} \\ -2.56 \times 10^{-4} & -2.47 \times 10^{-2} & 2.47 \times 10^{-2} \end{pmatrix} \text{eV}$$

- General TBM features:
  $|m_{e\mu}| = |m_{e\tau}|, \; m_{\mu\mu} = m_{\tau\tau}$
- Special for IH, m3=0: $|m_{\mu\mu}| = |m_{\mu\tau}|$
- Idea: Use $\mu_2 = -\mu_3$ and the associated couplings to fix $m_{\mu\mu} = m_{\tau\tau} = -m_{\mu\tau}$
- Employ $\lambda_{123} = \lambda_{132}$ and μ_1 to set the correct value for $m_{ee}, \; m_{e\mu}, \; m_{\mu\tau}$
- Keep λ_{231} small enough to not spoil $m_{\mu\mu} = m_{\tau\tau}$
- Kaon bound violated around m3=0.001eV

Couplings:

$\mu_1/\mu = 1.9 \times 10^{-8}$

$\mu_2/\mu = -4.7 \times 10^{-6}$

$\mu_3/\mu = 4.7 \times 10^{-6}$

$\lambda_{123} = 3.2 \times 10^{-4}$

$\lambda_{132} = 3.2 \times 10^{-4}$

$\lambda_{231} \sim 10^{-4}$

$(\tilde{m} = \mu = 100\,\text{GeV}, \; \tan\beta = 10)$

Only 4 couplings needed!

A simple flavor symmetry for IH, TBM

- Necessary suppression can be achieved by breaking of $Z_4 \times Z_8$ with breaking parameter $\epsilon \approx 10^{-1}$
- Associated charge assignments:

$$Q(L_1) = (2,5),\ Q(L_2) = (0,5),\ Q(L_3) = (3,2)$$

- Leads to the required suppression

$$\mu_1/\tilde{\mu} \sim \epsilon^7,\ \mu_2/\tilde{\mu} \sim \mu_3/\tilde{\mu} \sim \epsilon^5$$

$$\lambda_{123} \sim \lambda_{132} \sim \epsilon^3,\ \lambda_{231} \sim \epsilon^3$$

NH, TBM

$$m = \begin{pmatrix} 2.90\times10^{-3} & 2.90\times10^{-3} & -2.90\times10^{-3} \\ 2.90\times10^{-3} & 2.80\times10^{-2} & 2.21\times10^{-2} \\ -2.90\times10^{-3} & 2.21\times10^{-2} & 2.80\times10^{-2} \end{pmatrix}\,\mathrm{eV}$$

- Again: $m_{e\mu} = -m_{e\tau}$
- Tree level contribution requires $m^{tree}_{e\mu} \approx +m^{tree}_{e\tau}$
- Large sign-adjustment by trilinear loops for one element is needed
- Other element is generated purely at tree level
- Large hierarchy between the lambda couplings (sigificantly different)
- Kaon bound violated around m1=0.002eV

Couplings:

$\mu_1/\mu = -5.2\times10^{-7}$

$\mu_2/\mu = 3.9\times10^{-6}$

$\mu_3/\mu = 5.0\times10^{-6}$

$\lambda_{123} = -4.4\times10^{-3}$

$\lambda_{132} = -1.2\times10^{-6}$

$\lambda_{231} = 1.0\times10^{-4}$

$(\tilde{m} = \mu = 100\,\mathrm{GeV},\ \tan\beta = 10)$

6 couplings needed

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$\mathrm{IH}, \theta_{13} = 9^\circ$

$$m = \begin{pmatrix} 4.80 \times 10^{-2} & -5.13 \times 10^{-4} & -5.63 \times 10^{-4} \\ -5.13 \times 10^{-4} & 2.53 \times 10^{-2} & -2.41 \times 10^{-2} \\ -5.63 \times 10^{-4} & -2.41 \times 10^{-2} & 2.54 \times 10^{-2} \end{pmatrix} \mathrm{eV}$$

- Degeneracies between $|m_{e\mu}| = |m_{e\tau}|$ and $m_{\mu\mu} = m_{\tau\tau}$ lifted
- Again, tree level contribution to $m_{e\mu}$ has wrong sign
- Large sign-adjustment by the loops for this element is needed
- $m_{e\tau}$ is generated purely at tree level
- Large hierarchy in the lambda couplings reuired (opposite to TBM)
- Upper bound from Kaon decay relaxes to m3=0.01eV

Couplings:

$\mu_1/\mu = -1.1 \times 10^{-6}$

$\mu_2/\mu = -4.5 \times 10^{-6}$

$\mu_3/\mu = 4.8 \times 10^{-6}$

$\lambda_{123} = 9.3 \times 10^{-3}$

$\lambda_{132} = 1.1 \times 10^{-5}$

$\lambda_{231} = -1.1 \times 10^{-4}$

$(\tilde{m} = \mu = 100\,\mathrm{GeV},\ \tan\beta = 10)$

6 couplings needed

NH, $\theta_{13} = 9°$

$$m = \begin{pmatrix} 4.60 \times 10^{-3} & 8.20 \times 10^{-3} & 2.29 \times 10^{-3} \\ 8.20 \times 10^{-3} & 2.67 \times 10^{-2} & 2.16 \times 10^{-2} \\ -2.29 \times 10^{-3} & 2.16 \times 10^{-2} & 2.80 \times 10^{-2} \end{pmatrix} \text{eV}$$

- Degeneracies between $|m_{e\mu}| = |m_{e\tau}|$ and $m_{\mu\mu} = m_{\tau\tau}$ lifted
- Opposed to NH, TBM signs of tree level contributions correct
- Large deviation between the absolute values of $m_{e\mu}$ and $m_{e\tau}$ still needs to be generated by loop contributions
- Leads again to a large hierarchy in the lambda couplings
- Kaon bound violated around m1=0.005eV

Couplings:

$\mu_1/\mu = 4.1 \times 10^{-7}$

$\mu_2/\mu = 3.8 \times 10^{-6}$

$\mu_3/\mu = 5.0 \times 10^{-6}$

$\lambda_{123} = -5.3 \times 10^{-3}$

$\lambda_{132} = -1.5 \times 10^{-6}$

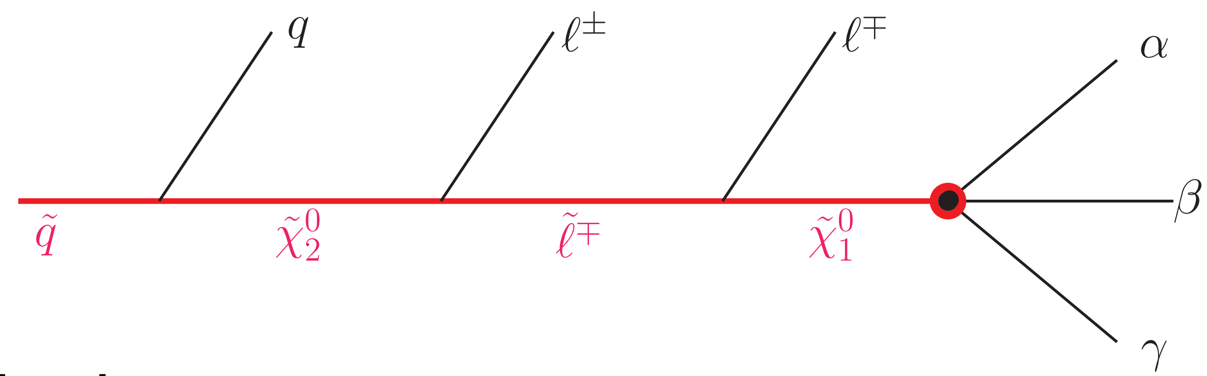
$\lambda_{231} = -8.3 \times 10^{-4}$

$(\tilde{m} = \mu = 100\,\text{GeV},\ \tan\beta = 10)$

6 couplings needed

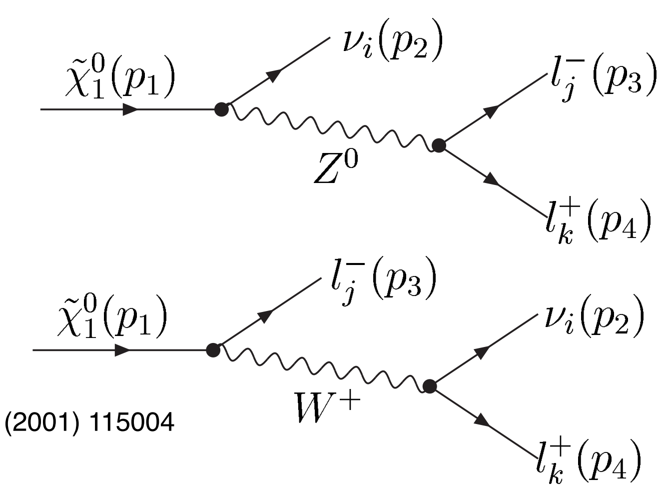
Collider relations

- Flavor structure of large LLE operators might be explorable in case of a neutralino LSP
  - 3 body decay $\tilde{\chi}_1^0 \to l^{\pm} l^{\mp} \nu$
  - different final state flavor
  - different invariant mass distributions



N. -E. Bomark, D. Choudhury, S. Lola, P. Osland, JHEP 1107 (2011) 070

- Bilinear operators lead to neutralino decay as well
  - 2 body decays $\tilde{\chi}_1^0 \to W^{\pm} l^{\mp},\ \tilde{\chi}_1^0 \to Z\nu$
  - can dominate



W. Porod, M. Hirsch, J. Romao, J. W. F. Valle, Phys. Rev. D63 (2001) 115004

- A detailed study of neutralino might distinguish different RPV models

Summary

- We presented an economic way, based on a flavor symmetry, to introduce RPV with only a hand full of independent couplings instead of ~100
  - Simplest realization leads to four parameters, tribimaximal mixing and inverted hierarchy
  - A large mixing angle θ_{13} and normal hierarchy can be accommodated in a six parameter realization
- General prediction: almost vanishing absolute mass scale for neutrinos
  - Tightly related to the non-observation of $K_L \rightarrow \mu e$
  - A positive signal of the upcoming $0\nu2\beta$ experiments implies inverted hierarchy
- Proposed flavor structure can lead to specific decays of a neutralino LSP at the LHC